NavIC and GPS State Vector as Tracking Sources for Flight Safety

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***Abstract*—For any launch vehicle flown with a flight termination system, the primary requirement is to know the current state vector of the vehicle from at least two different sources of tracking system out of which at least one should be independent of the vehicle navigation system. Radars operating in C-band and S-band are being currently used as primary source for tracking ISRO's launch vehicles. The maintenance and upkeep of these radars are very expensive. Till now, NavIC and GPS data are used only to correct the Inertial Navigation system(INS) data in ISRO. But, when INS loses its reference, this correction is not possible. To increase the tracking sources, this paper proposes to use the position and velocity information from NAVIC and GPS receivers directly for flight safety decision making purposes. In future, these tracking sources can also be used in autonomous flight safety systems to improve source diversity.**

Keywords— Tracking sources, Flight safety, instantaneous impact point(IIP), NavIC, GPS, PDOP, state vector, AFSS

I. INTRODUCTION

All launch vehicles are inherently dangerous whenever they contain fuel or oxidizer, or whenever explosive devices are installed, or whenever toxic chemicals or high-pressure gasses are on board. A fully loaded medium or heavy-lift launch vehicle has the chemical energy equivalent of a small nuclear warhead. Any rocket launch may become hazardous with the failure of one or more of its systems. Flight safety has the task of tracking all rocket systems during their ascent from the ground to its orbit, and terminating any flight before it poses a hazard to lives or property. The function of flight safety must balance the need to destroy an out-of-bounds launch vehicle before ground damage occurs, and the need to preserve the expensive space mission. To detect the failure and protect people and property from the hazards of the rocket launch, flight safety philosophy is laid out based on national and international policies on the acceptable risk levels to the public. In the conventional Flight safety decision making process, these philosophies are converted into graphics based user interfaces. The real time data from tracking and telemetry sources are monitored over this background information to ascertain the health of the launch vehicle and to take decision if required. The instantaneous impact point(IIP) is computed using *f*and*g* [4] algorithm from all these sources. IIP is an important tool in flight safety decision making.

II. FLIGHT TRACKING REQUIREMENTS

The flight tracking requirement based on NASA procedural documents [1],[2] are as follows:

For a vehicle that is flown with an Flight Termination System (FTS), the flight safety systems used to support a flight termination decision shall include at least two sources of vehicle tracking data, where the two sources are independent of each other and at least one of the sources is independent of the vehicle guidance system. The tracking data from each source shall be of sufficient quality to determine the vehicle's real-time position and instantaneous impact point throughout the period of time that the data is needed to support a flight termination decision. The specified sample rate(s) of the tracking system, including Telemetry and ground processing, shall ensure that the data delivered to ground processing systems is sufficient to ensure that a non-nominal flight can be detected and terminated prior to public endangerment or loss of flight control. All required tracking sources shall be independent of each other to the extent necessary to ensure that a failure of one tracking source does not adversely affect any required performance parameter of the other. The total system delay time, including delays in tracking system, data processing and RSO reaction time, shall ensure a non-nominal vehicle flight can be detected prior to vehicle breakup, loss of destruct capability or violation of destruct line criteria. The delay (data latency) introduced by each component or subsystem of the tracking system shall support the total system delay requirement. Any real-time tracking source(RTS) used for Range Safety shall have a singular reliability of 97 percent. The probability that an RTS tracking source produces real-time undetectable out-of-specification state vector data shall be less than 10-3. The probability of an RTS to show that a non-nominal vehicle is nominal must be less than 10-6.

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III. Current Sources Used For Flight Safety

The sources currently used for Flight safety decision making are based on tracking radars and Vehicle telemetry system. Two on-board C-Band transponders are provided in launch vehicle to enable accurate tracking. Each transponder is configured to accommodate two radars. With two on-board transponders, four ground based radars communicate with the launch vehicle and provide accurate position information about the launch vehicle. Two radars in skin mode are also configured to take care of failures of launch vehicle in the initial phase. Three precision C-Band radars are used in transponder mode to enable tracking with accuracy of 0.1mil in angle and 10m in slant range. The two skin mode radars operate in S-band. The telemetry system is based on a Redundant Strapdown Inertial Navigation system (RESINS). RESINS uses accelerometers and gyros data to arrive at the position information of the vehicle. In addition to position information, stage chamber pressure, body rates and body errors are also provided in telemetry data. Data from tracking radars is the primary source of information for RSO. Data from telemetry is secondary because when INS loses its reference, its state vector is not reliable. Stage chamber pressure and body rates data are only tertiary information. Any discrepancy in these data is only an alert and the subsequent failure should manifest in trajectory information to take a valid decision.

Radars data is available as range, azimuth and elevation for every 100ms.INS data is available as state vector in Earth Centered Inertial (ECI) frame. Both, Radars and INS data, are converted into state vector in Topocentric Relative (TPR) frame. The state vector in TPR frame is then converted into the required display parameters like IIP (latitude and longitude), Spherical ground range, Spherical Altitude, Relative velocity and Ground trace. The conversions are provided in reference [5]. Sensor data for chamber pressure, body rates, body errors are converted into engineering units and provided for display. Flight safety displays with radars and INS sources for ISRO launch vehicles are detailed in [6].

IV. Need for NavIC and GPS statevector as independent source

Existing launch vehicle navigation is generally based on attitude and acceleration sensing instrumentation that are subject to drift, initialization errors and failures. Thus, a launch vehicle can easily be under the control of a seemingly normal operating navigation system, yet be steering the launch vehicle along an incorrect and dangerous flight path. To cover this navigation system's weakness, NavIC based positioning system is used to correct the errors of the inertial navigation system. Aided inertial navigation involves the integration of the NavIC navigation solution with the inertial navigation solution to achieve an optimal navigation solution. But, when inertial navigation system fails due to failure of any of its sensors, then correction with NavIC data is not possible.

Radars are costly to maintain at high reliability levels. Even when launch is not there, radars have to be maintained for up-keeping its reliability. For every launch, radars are calibrated by tracking satellites, aircraft and balloon. The cost incurred in refurbishment of old radars, though marginally less than developing a new radar, is still high. Although when sufficient radars are available with redundancy, failure of one or two primary radars always induces doubt in flight safety decision making process. Since, NavIC and GPS state vectors are already being used for aiding INS, these state vectors may also be taken directly as a tracking source to increase the number of sources used for flight safety decision making.

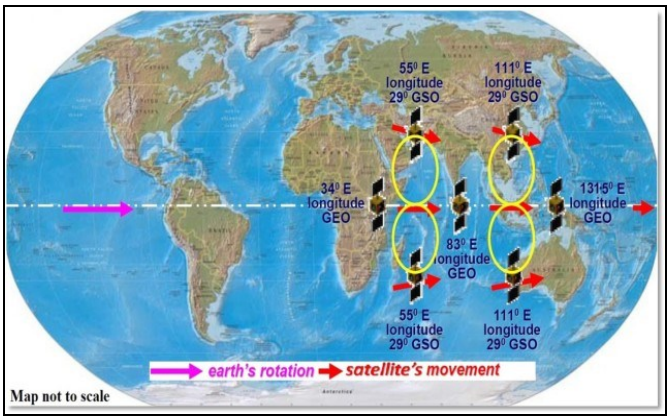
55° E longitude 29° GSO
111° E longitude 29° GSO
34° E longitude GEO
131.5° E longitude GEO
83° E longitude GEO
55° E longitude 29° GSO
111° E longitude 29° GSO
earth's rotation
satellite's movement
Map not to scale

Fig. 1. NavIC constellation

NavIC constellation consists of 7 Indian satellites as shown in Fig.1. Three of the seven satellites are located in geostationary orbit (GEO) at 32.5° East, 83° East, and 131.5° East longitude, approximately 36,000 km above earth surface. Remaining four satellites are in inclined geosynchronous orbit (GSO). Two of them cross equator at 55° East and two at 111.75° East longitude. Due to its orbital positioning, these satellites are theoretically visible to our launch vehicle till satellite injection.

Two antennae are available at diametrically opposite directions on the vehicle for both NavIC and GPS signal reception. This antennae positioning is to cater for visibility requirements for the entire duration of the flight. NavIC and GPS satellites are tracked in L1 as well as L5 bands. The sub-system which receives and processes NavIC and GPS data is independent of INS sub-system. The state vectors of INS, NavIC, GPS and Hybrid are received from the vehicle via two telemetry streams. All data are available in both streams. So if any one stream fails also, data is available in other stream. Therefore, even if any sensor in the INS system fails, the state vectors from NavIC and GPS state vectors will be available via vehicle telemetry.

V. NavIC and GPS performance analysis

NavIC and GPS state vectors are available in real-time in 1Hz interval. The state vectors are in ECEF frame. This data is converted into TPR frame as done for INS state vector. The main Achilles heel for navigation system data is the availability of data due to Position dilution of precision (PDOP) increase and random noises due to sudden change in acceleration of launch vehicle. For NavIC, the visibility of all the satellites are available right from lift-off till flight safety decision making duration. Instantaneous impact point(IIP) is computed from NavIC as well as GPS state vectors and are compared with the NavIC aided INS (NAINS) data to establish the usability of

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these state vectors in real-time for flight safety decision making. The data corresponding to two different types of missions, viz. Sun synchronous polar orbit (SSPO) and Geostationary Transfer Orbit (GTO) missions are analysed.

Fig 2 and Fig 3 represents the NavIC and GPS state vectors plotted in comparison with NAINS data as Range vs Altitude plots and Time vs Relative Velocity plots. It can be seen that the Range vs Altitude and Time vs Relative velocity plots are smooth with no spikes. The Range vs Altitude and Time vs Relative velocity plots show the present position of the launch vehicle to RSO and this constitutes the trajectory information.

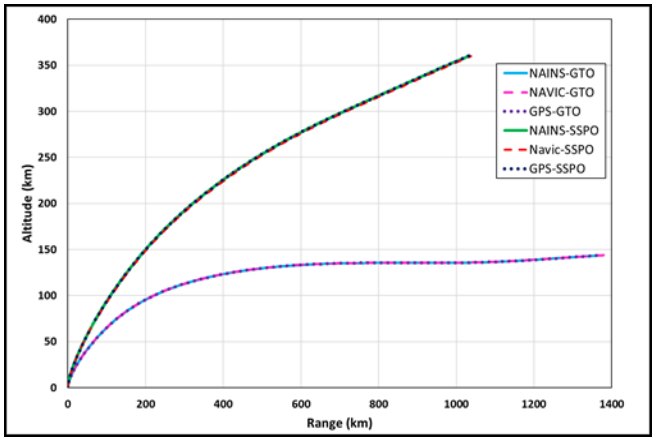

Fig. 2. Range vs Altitude

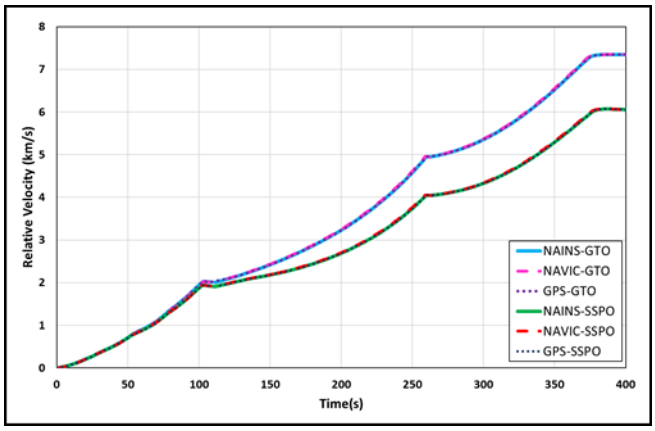

Fig. 3. Time vs Relative Velocity

Fig 4 and 5 shows the First difference plot of longitude and latitude of the IIP computed from NavIC, GPS and NAINS data. The first difference of IIP computed from NavIC and GPS are similar to NAINS data. This data provides confidence in computing IIP from these two sources.

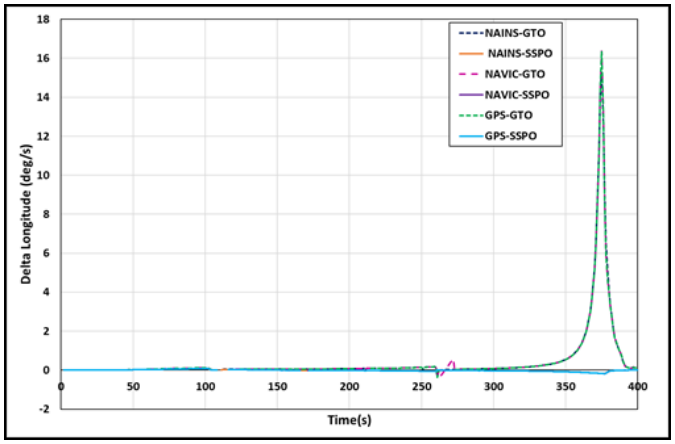

Fig. 4. Time vs Delta Longitude

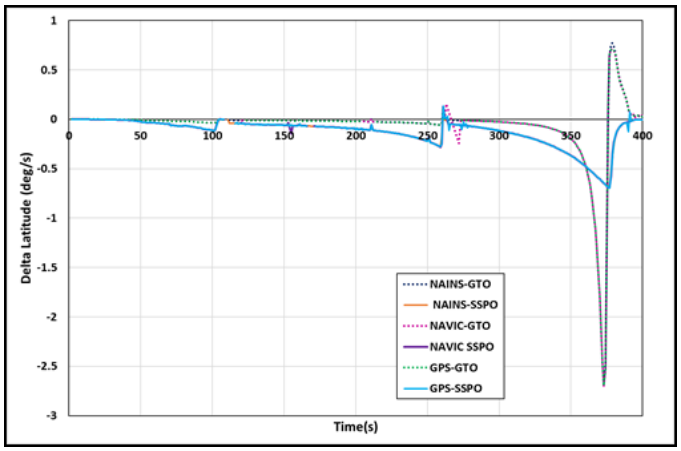

Fig. 5. Time vs Delta Latitude

Fig 6 shows the PDOP values of NavIC and GPS for both missions. Good PDOP values throughout the flight safety requirement duration assures the availability of good quality data from these sources. The PDOP values of NavIC for southward mission is smooth with only dip during heatshield separation. But for GTO mission, the PDOP has disturbances during stage separations also. The PDOP values for GPS are good even during stage separations for both kinds of missions. Therefore, NavIC and GPS data can be considered for IIP computation when the PDOP value is less than 5 and greater than one [7].

The main utility of the tracking sources for flight safety is to detect a failure. Therefore, the tracking source's behaviour during failure has to be analysed. The data of these state vectors during a failure is not available till date. Therefore, the duration when the stage tumbles after satellite separation is considered for analysis. The PDOP values for a typical GTO mission is plotted in Fig.7.

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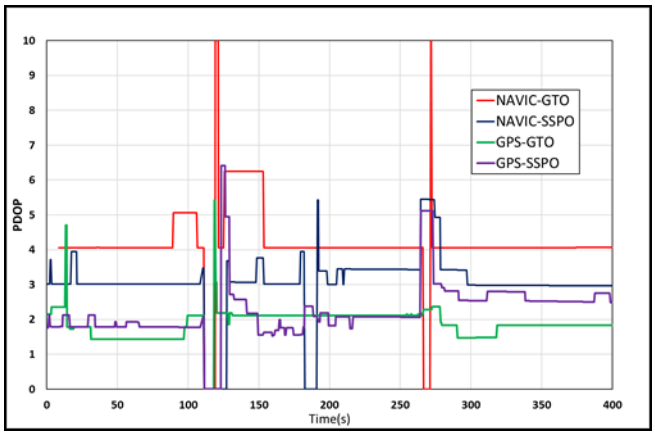

Fig. 6. Time vs PDOP values

It is seen that the PDOP values of GPS is good and the state vector quality is ensured, whereas NavIC PDOP values are not up to the mark. GPS is designed in such a way that even with a single satellite failure, the PDOP does not exceed six for more than 25 min/day for a user constraint on satellite elevation angles of 5° or more [7]. Also, for any latitude, there are at least seven satellites in view. Therefore, GPS has better PDOP than NavIC. This is the one set of data available for NavIC and since the data pertains to GTO launch, the number of satellites visible after satellite separation may be less than optimum to arrive at proper position fix. Before including NavIC for flight safety decision making, more data is required with failure mode cases. Till that time, Hybrid state vectors which include both NavIC and GPS satellites for position computation may be proposed to be used for Flight safety decision making.

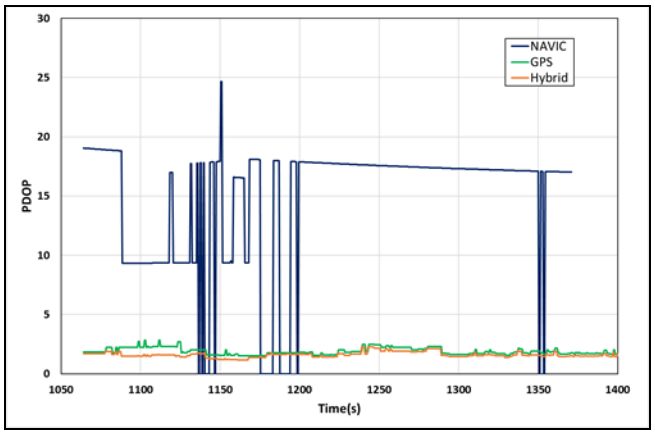

Figure 7: PDOP during Tumbling phase

VI. Autonomous Flight Safety System (AFSS)

AFSS utilizes on-board sensors and processors to emulate the human decision-making process using rule-based software logic and can dramatically reduce safety response time during critical launch phases. The Range Safety flight path nominal trajectory, its deviation allowances, limit zones, and other flight safety rules are stored in the on-board computers. Position, velocity, and attitude data obtained from on-board Global Positioning System (GPS) and Inertial Navigation System (INS) sensors are compared with these rules to determine the appropriate action to ensure that people and property are not jeopardized. If NavIC and GPS state vectors are successfully used for conventional Flight safety decision making, then these sources can be confidently used in AFSS also thereby increasing the source diversity.

VII. Conclusion

The performance of NavIC and GPS state vectors for the past missions were analysed with respect to the quality and availability perspective. During stage separation events, the data from these sources should not be considered as the PDOP is more. Based on the tumbling stage PDOP study, NavIC data cannot be used during tumbling phase. GPS or Hybrid data can be used during tumbling phase. NavIC will be available via telemetry even when INS loses its reference. In future, when cost cutting is brought about by commercial space operations, these sources can be used in autonomous flight safety system for source diversity.

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